REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
30-10-2012	Final Report	1-Jul-2007 - 19-Mar-2012

4. TITLE AND SUBTITLE	
Fast, Automated, 3D Modeling of Building Interiors	5a. CONTRACT NUMBER W911NF-07-1-0471
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Dr Avideh Zakhor	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of California - Berkeley Sponsored Projects Office The Regents of the University of California Berkeley, CA 94704 -5940	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 53259-MA.7

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

Fast, automated, photo-realistic 3D modeling of indoor environments is useful in military reconnaissance applications and civilian emergency response applications. Over the past five years, we have developed a human operated ambulatory backpack system equipped with 2D laser range finders, IMU and cameras in order to capture geometry and texture of the building interiors. The main advantage of our approach over a wheeled system is its capability to model uneven surfaces such as staircases; however our system requires 6 DoF pose recovery, rather

15. SUBJECT TERMS

3D modeling, mapping, surface reconstruction, Pose recovery, localization 6 Dof, watertight, texture mapping loop closure

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Avideh Zakhor
UU	UU	UU	UU		19b. TELEPHONE NUMBER 510-643-6777

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

1.00 Victor Sanchez, Avideh Zakhor. Planar 3D Modeling of Building Interiors from Point Cloud Data, International Conference on Image Processing. 2012/09/30 03:00:00, . : ,

2.00 John Kua, Nicolas Corso, Avideh Zakhor. Automatic Loop Closure Detection Using Multiple Camerasfor 3D Indoor Localization, IS&T/SPIE Electronic Imaging 2012. 2012/01/22 03:00:00, . : ,

3.00 Michael Anderson, Kurt Keutzer, Avideh Zakhor. TEXTURING LONG PLANAR SURFACES WITH IMPRECISE CAMERA POSES FORINDOOR 3D MODELING, International Conference on Image Processing. 2012/09/30 03:00:00, . : ,

4.00 Norihiko Kawai, Avideh Zakhor, Tomokazu Sato, Naokazu Yokoya. Surface Completion of Shape and Texture Based on Energy Minimization, ICIP 2011. 2011/09/11 03:00:00, . : ,

5.00 Timothy Liu, Matthew Carlberg, George Chen, Jacky Chen, John Kua, Avideh Zakhor. Indoor Localization and Visualization Using a Human-Operated Backpack System, 2010 International Conference on Indoor Positioning and Indoor Navigation. 2010/09/15 03:00:00, . : ,

6.00 George Chen, John Kua, Stephen Shum, Nikhil Naikal, Matthew Carlberg, Avideh Zakhor. Indoor Localization Algorithms for a Human-Operated Backpack System, 3D Data Processing, Visualization, and Transmission 2010. 2010/05/17 03:00:00, . : ,

TOTAL: **6**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Final Report for ARO Grant W911NF-07-1-0471
P.I. Avideh Zakhor, U.C. Berkeley

I. Peer reviewed Conference Proceedings

[1] P. Cheng, M. Anderson, S. He, A. Zakhor, **"Texture Mapping 3D Planar Models of Indoor Environments with Noisy Camera Poses,"** SPIE electronic imaging conference, Multimedia content Access. Burlingame, California, February 2013. [Adobe PDF]

[2] E. Liang, A. Zakhor, **"Structuring a Sharded Image Retrieval Database,"** SPIE electronic imaging conference, Multimedia Content Access. Burlingame, California, February 2013. [Adobe PDF]

[3] E. Turner, A. Zakhor, **"Watertight As-Built Architectural Floor Plans Generated from Laser Range Data,"** 3DIMPVT, October 2012, Zurich, Switzerland. [Adobe PDF]

[4] E. Turner, A. Zakhor, **"Sharp Geometry Reconstruction of Building Facades Using Range Data,"** International Conference on Image Processing, Orlando, Florida, Sep. 2012. [Adobe PDF]

[5] V. Sanchez, A. Zakhor, **"Planar 3D Modeling of Building Interiors from Point Cloud Data,"** Submitted to International Conference on Image Processing, Orlando, Florida, Sep. 2012. [Adobe PDF]

[6] S. Lagüela, J. Arnesto, P. Arias, and A. Zakhor, **"Automatic Procedure for the Registration of thermographic Images with Point Clouds,"** Presented at International Society for Photogrammetry and Remote Sensing (ISPRS), Melbourne, Australia, 2012. [Adobe PDF]

[7] J. Kua, N. Corso, A. Zakhor, **"Automatic Loop Closure Detection Using Multiple Cameras for 3D Indoor Localization,"** to be presented at IS&T/SPIE Electronic Imaging 2012, Burlingame, California, January 22-26, 2012. [Adobe PDF]

[8] X. Shi, A. Zakhor, **"Fast Approximation for Geometric Classification of Lidar Returns,"** ICIP 2011, Brussels, Belgium, September 11-14, 2011. [Adobe PDF]

[9] N. Kawai, A. Zakhor, T. Sato, N. Yokoya, **"Surface Completion of Shape and Texture Based on Energy Minimization,"** ICIP 2011, Brussels, Belgium, September 11-14, 2011. [Adobe PDF]

[10] A. Hallquist and A. Zakhor, " **Single View Pose Estimation of Mobile Devices in Urban Environments",** to appear in Workshop on Applications of Computer Vision (WACV), January 2013, Clearwater, Florida

[11] R. Garcia, and A. Zakhor, **" Geometric Calibration for a Multi-Camera-Projector System"** to appear in Workshop on Applications of Computer Vision (WACV), January 2013, Clearwater, Florida.

II. Presentations

Invited keynote speech on Fast, automated, photorealistic 3D modeling of building interiors, North Carolina State University, Raleigh, NC, September 2011.

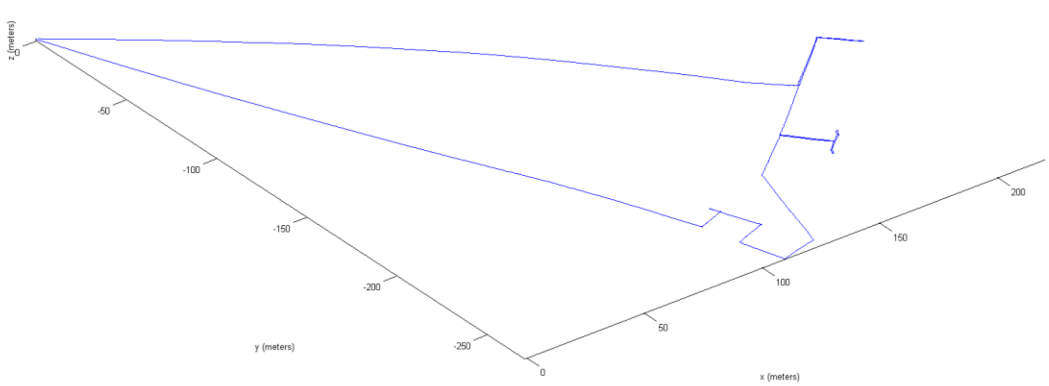
III. Personnel Supported

Avideh Zakhor, faculty
Nicolas Corso, Graduate student
Eric Turner, Graduate student
Peter Cheng, Graduate student

IV. Technology Transfer

Honoring request from Army personnel Greg Spurlock, our team spent few days in April to collect data for some of the tunnels in the Fort Hood Military Post in Killeen, Texas. Specifically, on April 23rd and 24th 2012, experiments were carried out in two separate underground tunnel systems. The tunnel systems, referred to as Tunnel 92050 and Tunnel 92026, have nearly identical layout, with the main difference being that they are nearly mirrored complements to one another. The tunnel complexes consisted of long narrow passageways with illumination ranging from bright florescent to non-existent. Head lamps and flashlights were needed for a few sections of Tunnel 92026. Geometrically, aside from the curved ceiling, the tunnels were long and devoid of geometric features. This made the test conditions quite challenging for our laser backpack system which uses scan matching to localize and build 3D models.

For each of the tunnel systems we collected three data sets. Since the layouts of Tunnel 92050 and Tunnel 92026 were nearly mirror images, the path planning for each was identical. The datasets were collected such that they got progressively longer and more complicated. The first dataset was a loop from the tunnel system. The basic structure of the estimated path is shown in the image below.



The walking time for Tunnel 92050 and Tunnel 92026 was 12.5 and 13.3 minutes respectively. The total estimated length for this configuration was 896.75 for Tunnel 92050 and 973.16 meters for Tunnel 92026. Seen in Figures 1 through 3 below are screenshots of the reconstructed point cloud resulting from data taken from this section of Tunnel 92050.

Figure 1: Screenshot of the 3D reconstructed point cloud for Tunnel 92050

Figure 2: Screenshot for a close up view of the long featureless tunnels present in the datasets

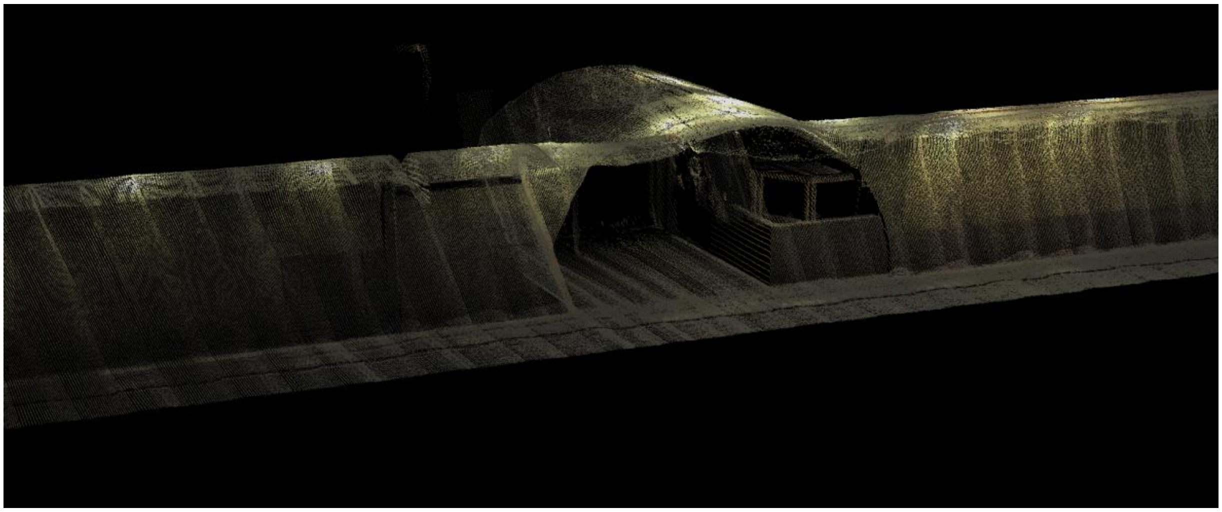


Figure 3: Close up view of some of the details visible in an interesting subsection of the dataset.

The second set of experiments we ran was similar to the first in that we explored the same area. We entered through one of the long tunnels, explored some of the inside areas, and then returned to the start. The difference, however, was that we explored a larger area inside the system and returned through the same tunnel at which we entered. Exploration of Tunnel 92050 during this experiment took 15.9 minutes and the estimated path length was 1147 meters. Tunnel 92026 took 18.6 minutes to explore and the estimated path length was 1351 meters. Figure 4 below is a screenshot of the Tunnel 92026 reconstructed from the second experiment configuration.

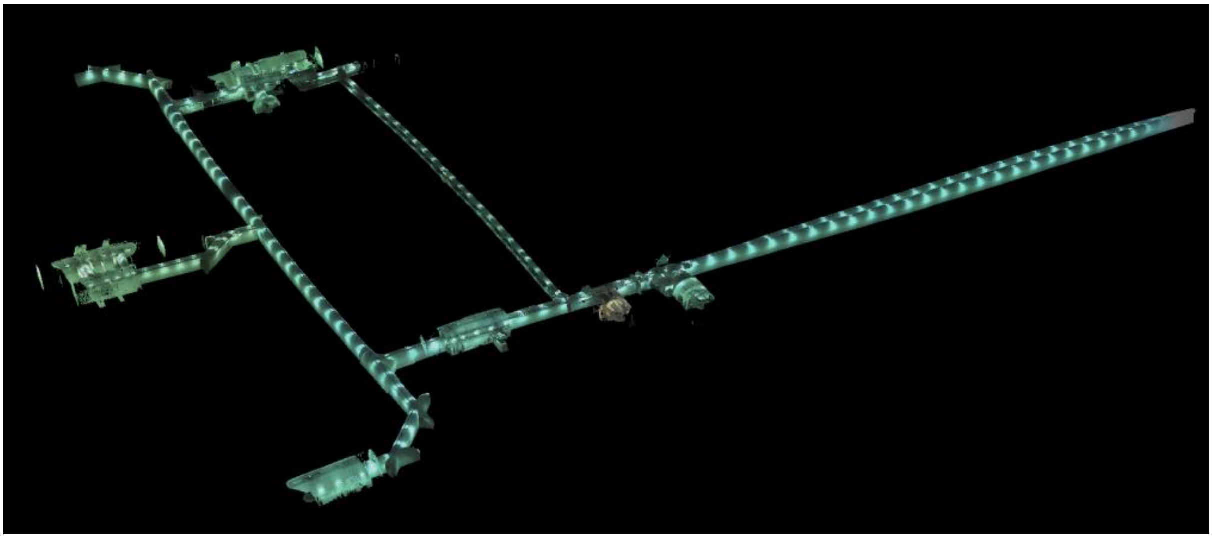


Figure 4: Screenshot of the reconstructed point cloud for Tunnel 92026.

The final experiment we ran was the most complex of the three. We began the run already in the tunnel system and explored all each of the inner portions of the tunnels in full. This included all areas that we were authorized to enter and in which our backpack system could fit. The running time for

Tunnel 92050 was 19.9 minutes and the walking distance was estimated to be 1204 meters. For Tunnel 92026 the equivalent statistics are 21.2 minutes and 1338.7 meters. Figure 5 below is the estimated system trajectory from Tunnel 92026.

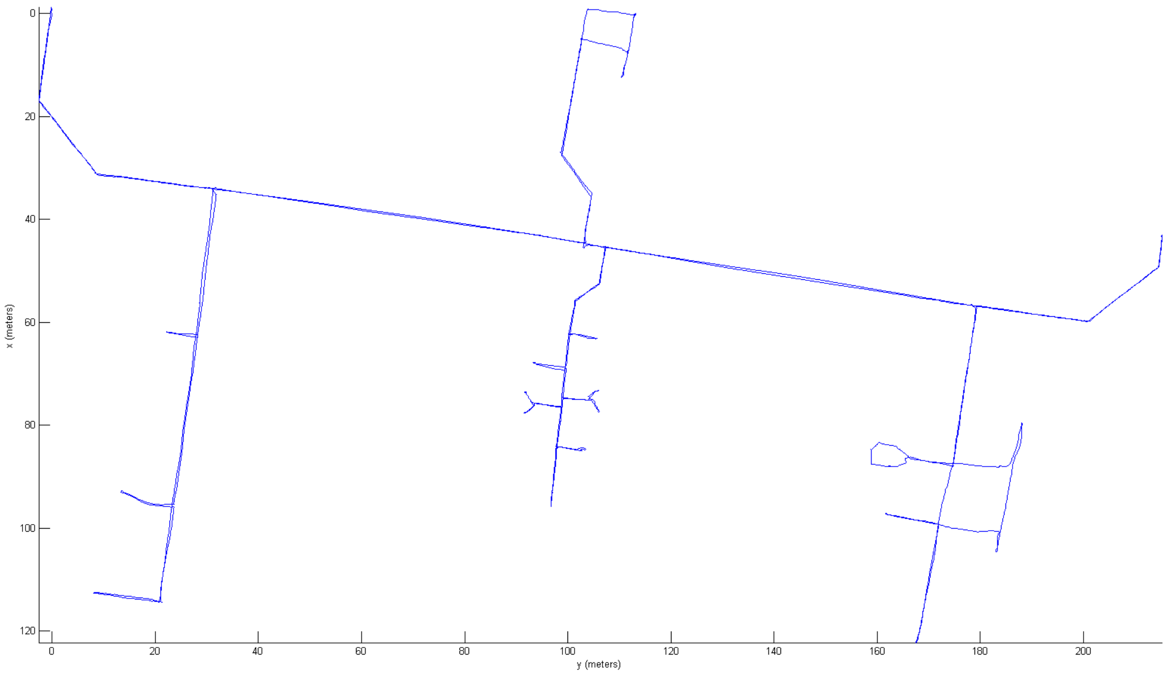


Figure 5: Estimated Trajectory for Tunnel 92026

Reconstructing the point cloud from this section yields over one hundred million points for this length of running time. Figure 6 below is a zoomed out view of this section of the tunnel system.

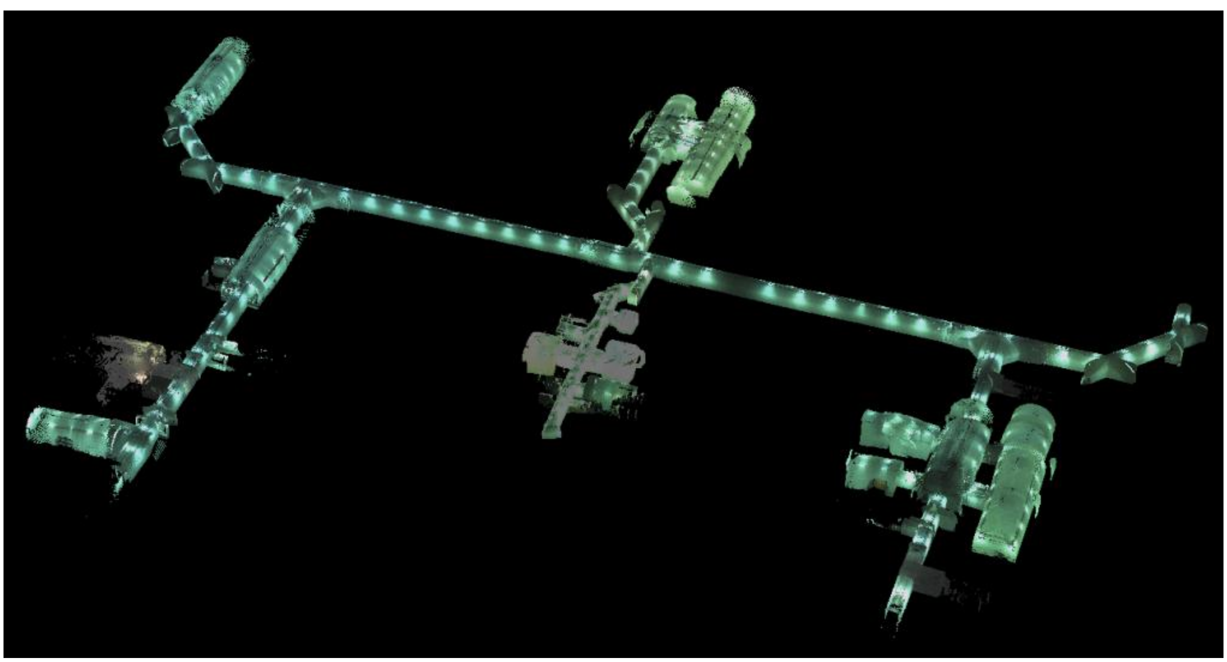


Figure 6: Zoomed out view of the Tunnel 92026

Figure 7 shows a close up view of the intersection of two of the tunnels in the above point cloud. The ceiling has been removed for visualization purposes.

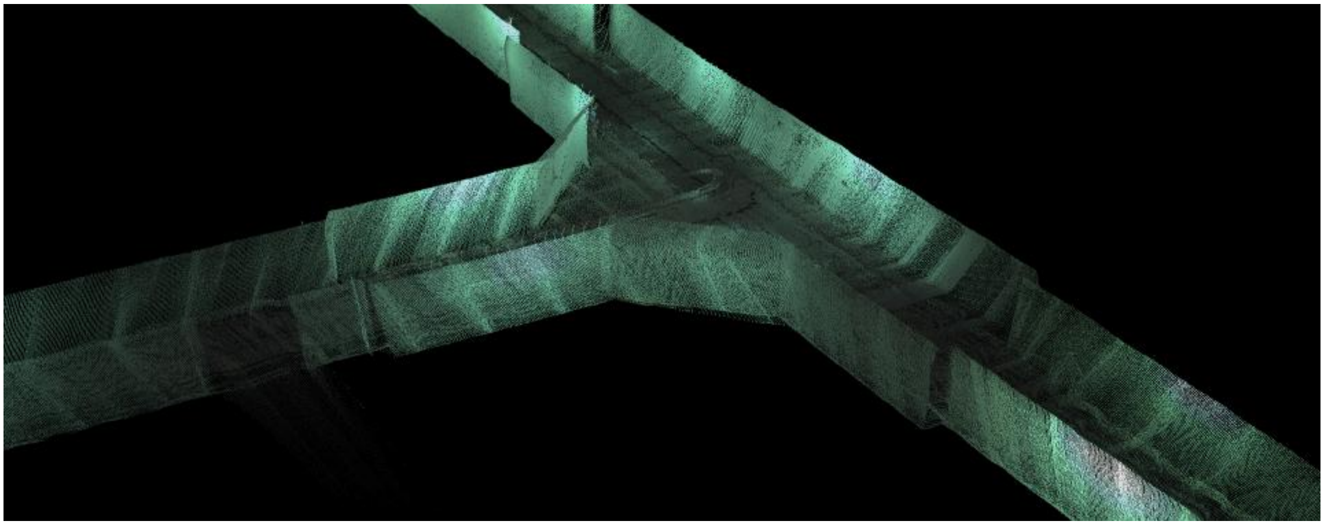


Figure 7: Close up view of the intersection of two of the tunnels in the point cloud of Figure 6.

Using the point cloud from this dataset, a surface watertight reconstruction was performed for Tunnel 92050 at a resolution of 10 centimeters. Figure 8 shows the macro view of the reconstructed model.

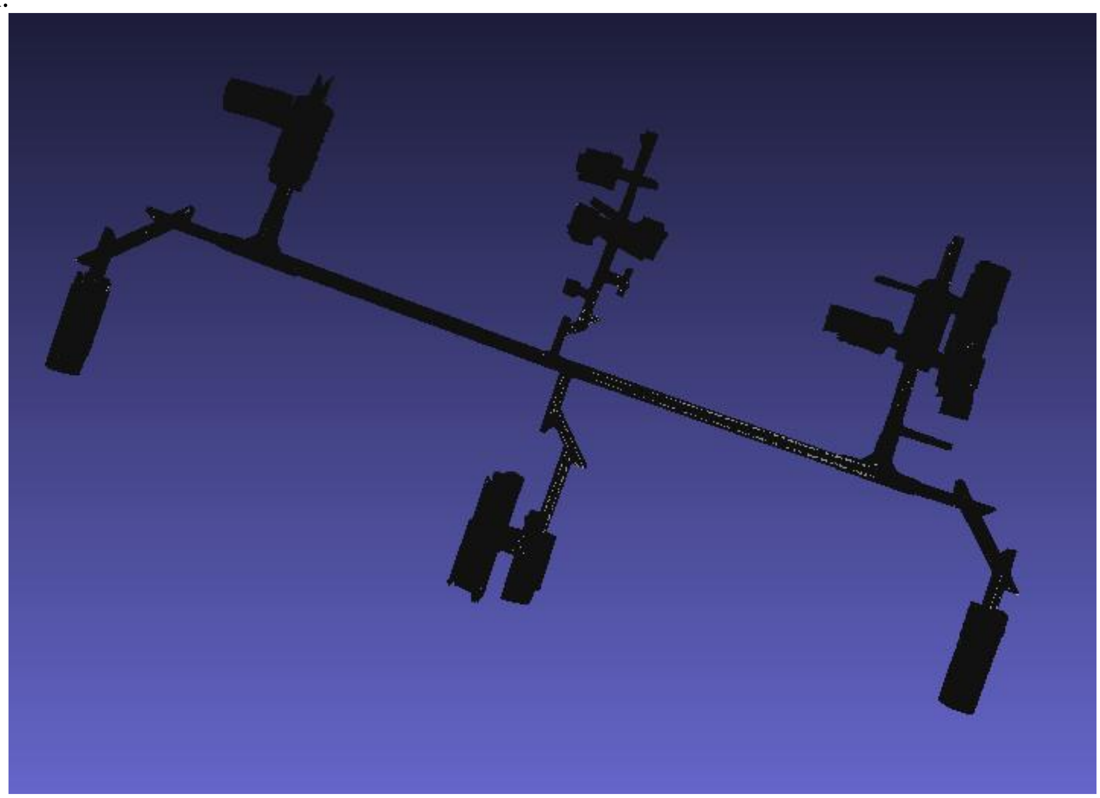


Figure 8: Macro view of the reconstructed surface model for Tunnel 92050.

Figure 9 shows a screenshot of the intersection of two tunnels from the inside of the tunnels.

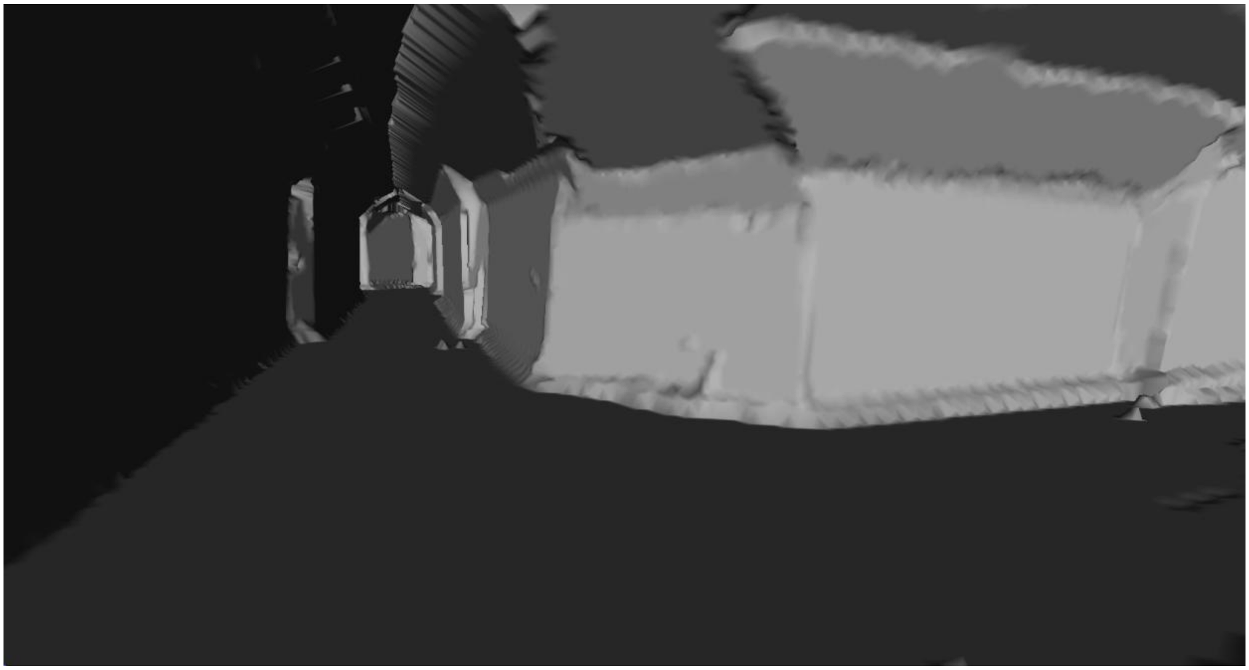


Figure 9: Screenshot of the intersection of two tunnels from the inside of the tunnels.

Finally, Figure 10 shows a view of one of the chambers from the inside.

Figure 10: A view of one of the chambers in Figure 9 from the inside.

V. Scientific Progress and Accomplishments

- In the area of model construction, we have developed an automatic system for planar 3D modeling of building interiors from point cloud data generated by range scanners [5]. This is motivated by the observation that most building interiors may be modeled as a collection of planes representing ceilings, floors, walls and staircases. Our proposed system, which employs model-fitting and RANSAC, is capable of detecting large-scale architectural structures, such as ceiling and floors, as well as small scale architectural structures, such as staircases. We have experimentally validated our system on a number of challenging point clouds of real architectural scenes.

- We have developed an algorithm that generates as-built architectural floor plans from point clouds generated from our 3D indoor modeling system [3]. We do so by separating the floors of the LiDAR scan of a building, selecting a representative sampling of wall scans for each floor, and triangulating these samplings to develop a watertight representation of the walls for each of the scanned areas. Curves and straight line segments are fit to these walls, in order to mitigate any registration errors from the original scans. This method is not dependent on the scanning system and can successfully process noisy scans with non-zero registration error. Most of the processing is performed after a dramatic dimensionality reduction, yielding a scalable approach. We have demonstrated the effectiveness of our approach on a three story point cloud from a commercial building as well as on the lobby and hallways of a hotel.

- Applying textures to these models is an important step in generating photorealistic visualizations of data collected by modeling systems. Camera pose recovery in such systems often suffers from inaccuracies, resulting in visible discontinuities when successive images are projected adjacently onto a plane for texturing. In the last year, we have developed two approaches to reduce discontinuities in texture mapping 3D models made of planar surfaces [1]. The first one is tile based and can be used for images and planes at arbitrary angles relative to each other. The second one results in a more seamless texture, but is only applicable where camera axes for images are closely aligned with plane normals of the surfaces to be textured. The effectiveness of our approaches are demonstrated on two indoor datasets.

- We have developed a surface completion method to generate plausible shapes and textures for missing regions of 3D models [9]. The missing regions are filled in by minimizing two energy functions for shape and texture, which are both based on similarities between the missing region and the rest of the object; in doing so, we take into account the positive correlation between shape and texture. We have demonstrated the effectiveness of the proposed method experimentally by applying it to two models.

- We have developed a method for detailed geometry reconstruction of building facades in an urban environment, given a 3D point-cloud of LiDAR range data [4]. Our approach separates planar faces and interpolates their shape with Moving Least-Squares (MLS) sampling. A method is then proposed to reconstruct occluded areas of the building whereby gaps in the building surface are modeled with axis-aligned planes fit to the gap boundary vertices. This approach reconstructs unsampled areas of building surfaces under the assumption that buildings have 3D

rectilinear, axis-aligned features. We have demonstrated the effectiveness of our approach on a number of building facades.

- We have developed a procedure for the automatic registration of thermographies with laser scanning point clouds [6]. Given the heterogeneous nature of the two modalities, we propose a feature-based approach, satisfying the requisite that extracted features have to be invariant not only to rotation, translation and scale but also to changes in illumination and dimensionality. As speed and minimum operator interaction are prerequisites for the viability of the process in the building industry, our automatic registration procedure includes automatic feature extraction with no human intervention. With this aim, a line segment detector is used to extract 2D lines from thermographies, and 3D lines are extracted through segmentation of the point cloud. Feature-matching and the relative pose between thermographies and point cloud are obtained from an iterative procedure applied to detect and reject outliers; this includes rotation matrix and translation vector calculation and the application of the RANSAC algorithm to find a consistent set of matches. An automatically textured thermographic 3D model is the expected result of these procedures once the point cloud is filtered and triangulated.

- We have developed a technique which uses gridded approximate nearest neighbor searches for fast classification of geometric features in large LiDAR point clouds [8]. The underlying algorithm exploits spatial hashes and the forgiving nature of PCA as a part of geometric classification. We show a factor of 10-20 speed up for both actual and simulated point clouds with little or no loss in classification performance. Our approach is applicable to both uniform and variable–density aerial LiDAR datasets.

- We developed a calibration method for multicamera-projector systems in which sensors face each other as well as share a common viewpoint. We use a translucent planar sheet framed in PVC piping as a calibration target which is placed at multiple positions and orientations within a scene. In each position, the target is captured by the cameras while it is being illuminated by a set of projected patterns from various projectors. The translucent sheet allows the projected patterns to be visible from both sides, allowing correspondences between devices that face each other. The set of correspondences generated between the devices using this target are input into a bundle adjustment framework to estimate calibration parameters. We demonstrate the effectiveness of this approach on a multiview structured light system made of three projectors and nine cameras. Details of this approach can be found in [11].